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Evaporation over the Baltic Sea as an Example of a Semi-Enclosed Sea

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Abstract

Evaporation is a major term in the energy and water cycle of the Baltic Sea. Wide areas of a semi-enclosed sea like the Baltic Sea belong to the coastal zone, which is a transition zone from the different roughnesses and thermal properties of the open sea and the land surfaces. This causes that wind speeds in coastal areas are generally lower than over the open sea for the same geostrophic wind speeds somewhat dependent on the wind direction relative to the coast. Furthermore the evaporation is hampered by ice, which covers parts of the Baltic Sea during winter time and is more prevalent near the coast. Sea ice and the influence of the coast on the wind speed reduce evaporation by up to about 7 to 8% each. The resulting evaporation is of the same order as previous estimates and shows similar spatial and temporal patterns, but uncertainties remain. It is shown that these depend mainly on the boundary layer parameterization used to calculate the evaporation.

Zusammenfassung

Die Verdunstung über der Ostsee als Beispiel für ein Randmeer

Die Verdunstung ist eine wichtige Komponente des Wasser- und Energiekreislaufes der Ostsee. In Randmeeren wie der Ostsee gehören weite Teile zu den küstennahen Gebieten, die eine Übergangszone zwischen den unterschiedlichen Rauhigkeiten und thermischen Eigenschaften der offenen See und der Landoberfläche darstellen. Bei gleichen geostrophischen Windverhältnissen sind daher die Windgeschwindigkeiten in diesen Regionen geringer als auf der offenen See, was zu einer Verringerung der Verdunstung um bis zu 8% führt. Eine weitere Reduktion der Verdunstung von bis zu 7% ergibt sich durch die Berücksichtigung von Meereis, welches im Winter weite Teile der nördlichen Ostsee bedeckt. Die bei der Berücksichtigung beider Effekte resultierende mittlere Verdunstung stimmt gut mit früheren Untersuchungen überein und zeigt eine ähnliche räumliche und zeitliche Variation. Die verbleibenden Unsicherheiten sind deutlich geringer als die Unterschiede in der mittleren Verdunstung, die sich aus der Verwendung unterschiedlicher Parameterisierungsansätze für die Berechnung der Verdunstung ergeben.

1 Introduction

Water is a necessary condition for life on earth. A possible climate change might influence the availability of water regionally and will affect both economies and ecologies. Most of the water found on land has been evaporated from the oceans and transported by the atmospheric circulation towards the continents, where it finally precipitates. Although the oceans make up more than 70% of the earth's surface, knowledge about rates of evaporation and precipitation is still meager (e.g. Austin and Geotis, 1980). The main reason is the sparsity of direct measurements due to the small number of reliable precipitation measurements and the difficulty of measuring the evaporation on ships. Measurements of rain over land are easier to handle than over sea on running ships mainly due to lesser wind speeds relative to the rain gauges, but the inhomogenity of the observation network (e.g. Groisman and Legates, 1995) still leaves large gaps over the globe. That was the background for BALTEX (Baltic Sea experiment), which will explore, model and quantify various processes determining the variability in space and time of the energy and water cycle over the Baltic Sea and its catchment area. In the present study the evaporation over the Baltic Sea is investigated. As mentioned above direct measurements of evaporation over the sea are usually not available. Therefore fluxes of water vapor E were calculated using a bulk parameterization according to

$$E = -\rho \, C_E \, U_{10} \, \Delta q \tag{1.1}$$

by using synoptic standard observations of pressure, wind speed, air temperature, humidity and water temperature. Here ρ is the air density, C_E is the bulk transfer coefficient for water vapor, U_{10} is the mean wind speed at 10 m height and Δq is the mean air-sea difference of the specific humidity. The bulk transfer coefficients for neutral stability and the correction for stability have been adopted from Large and Pond (1981 and 1982).

To estimate the influence of the type of parameterization on the turbulent fluxes two more schemes were applied to the data:

- the Liu, Katsaros and Businger model (1979) in the formulation of Liu and Blanc (1984), using the drag coefficients of Kondo (1975) and in a second run those of Smith et al. (1992).
- a model using bulk coefficients for sensible heat and water vapor given by DeCosmo et al. (1996) and the drag coefficients of Smith (1980); in a second run again drag coefficients of Smith et al. (1992) were used. Correction for stability was done according to Smith (1988).

2 Data

Synoptic observations of voluntary observing ships and weather stations were provided by the Deutscher Wetterdienst for the period from 1992 to 1994, every 6 hours. The total number of ship observations is approximately 18500 corresponding to only 16 observations per day. These observations are concentrated along the shipping routes; in general observation densities are highest in the south west parts of the Baltic Sea (Figure 1). Due to the sparsity of the ship reports and their inhomogeneous distribution, leaving large gaps over the Baltic Sea, geostrophic wind fields were analyzed by using data from both ship and land observations. Wind speeds at a height of 10 m, needed to calculate evaporation using a bulk parameterization (Eq. (1.1)), were estimated from geostrophic winds by applying ageostrophic coefficients. The method is described in detail in Section 3.

The observational data were interpolated on a regular grid point field. The resolution is 1° in both the zonal and longitudinal direction.

The geostrophic surface winds were analyzed using an interpolation scheme developed by the Institut für Meereskunde (IfM) Kiel (Ennenga, 1985, and Bumke and Hasse, 1989). The analysis scheme is based on the polynomial method (Panofsky, 1949) and fits locally a second order pressure surface to both wind and pressure observations:

$$p^* = a_{00} + a_{10}x + a_{20}x^2 + a_{11}xy + a_{01}y + a_{02}y^2 \tag{2.1}$$

where x and y are the distances in the north and east directions between the positions of observations and grid points. The estimated parameters are marked with an asterix. The pressure field is related geostrophically to the wind field. This requires the application of a boundary layer parameterization to the surface wind observations to get geostrophic winds. For this purpose a stability dependent approach was used (Luthardt and Hasse, 1981), derived from situations with onshore winds in the German Bight. Because of a possible orographic influence only ship observations more than 100 km distant from the coast were used for interpolation. The geostrophic wind components u_g^* and v_g^* are given by:

$$u_g^* = \frac{a_{01} + 2a_{02}y + a_{11}x}{f\rho} \tag{2.2}$$

$$v_g^* = \frac{a_{10} + 2a_{20}x + a_{11}y}{f\rho} \tag{2.3}$$

Here f is the Coriolis parameter. The polynomial (2.1) is solved by minimizing the sum S:

$$S = (1-W)\sum_{k=1}^{n} C^2(p-p^*)^2 \tag{2.4}$$

$$+W\sum_{l=1}^{m} C^2((u_g-u_g^*)^2 + (v_g-v_g^*)^2)$$

where C is a Cressman-function, which describes the decreasing influence of an observation with increasing distance to the gridpoint (Cressman, 1959). W weights the relative influence of pressure and wind observations; for analysis $W = 0.3$ was choosen.

Due to the sparsity of ship observations additional information from coastal stations was required. Interpolations of dew point, air and water temperature were done by simple linear averaging over areas of 2° latitude times 2° longitude, again using information from both ships and coastal stations. Interpolated fields of dew point and air temperature were used to

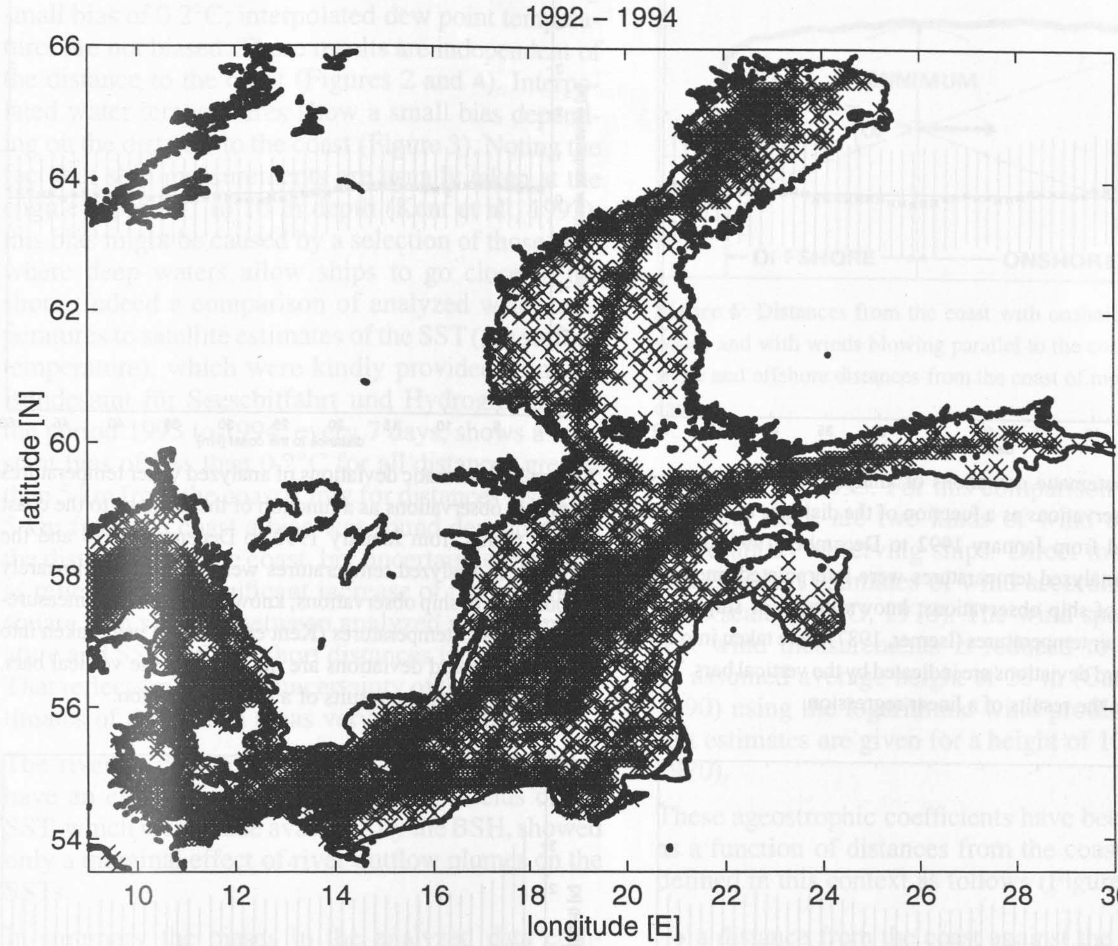

Figure 1: Distribution of wind observations by ships over the Baltic Sea in the period from January 1992 to December 1993.

compute fields of relative humidity. Due to the insufficient number of observations, water temperatures were further averaged over 5 days.

The analyzed grid point fields were compared to the ship observations. For that purpose the analyzed values were interpolated linearly to the ships' positions.

It is to be expected that interpolated air temperature fields at sea will be mainly influenced by the observations or measurements of the coastal stations used for analysis. For instance interpolated air temperatures might change from land to sea as a function of the distance from the coast and air sea temperature difference (Smith and MacPhersson, 1986), which implies that they are strongly affected by the direction of the wind relative to the coast. In fact a linear regression of differences of analyzed (T_{ana}) to observed air temperatures at sea on analyzed air-sea temperature differences ΔT_{ana} has a correlation coefficient of 0.71 and results in corrected air temperatures at sea (T_{air}) according to

$$T_{air} = T_{ana} - 0.4 \cdot \Delta T_{ana} \tag{2.5}$$

This reduces the scatter between interpolated and observed air temperatures at sea by some 50%. No similar correlation was found for relative humidity or for water temperature estimates.

Specific humidities of the air were calculated from relative humidities and air temperatures corrected according to Eq. (2.5); specific humidities at the sea surface were calculated from analyzed water temperatures assuming 100 % relative humidity. The influence of salinity on the saturation vapour pressure was neglected.

The correlation coefficients of interpolated dew points and air and water temperatures to ship observations are 0.97, 0.97 and 0.98. The biases between

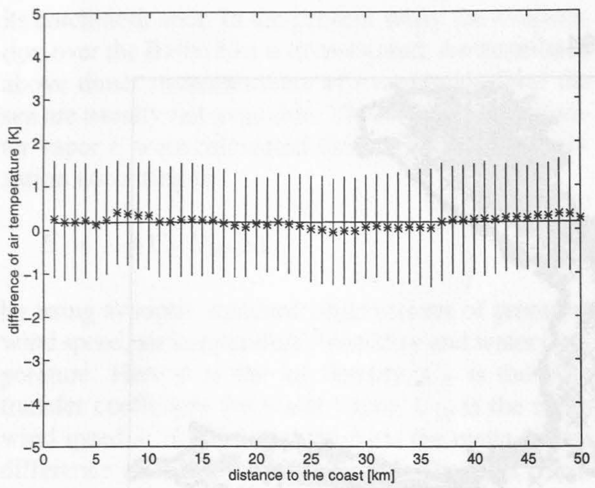

Figure 2: Systematic deviations of analyzed air temperatures from ship observations as a function of the distance to the coast for the period from January 1992 to December 1994 and the Baltic Sea. Analyzed temperatures were interpolated linearely on positions of ship observations; known biases of ship measurements of air temperatures (Isemer, 1987) were taken into account. Standard deviations are indicated by the vertical bars. The full line gives the results of a linear regression.

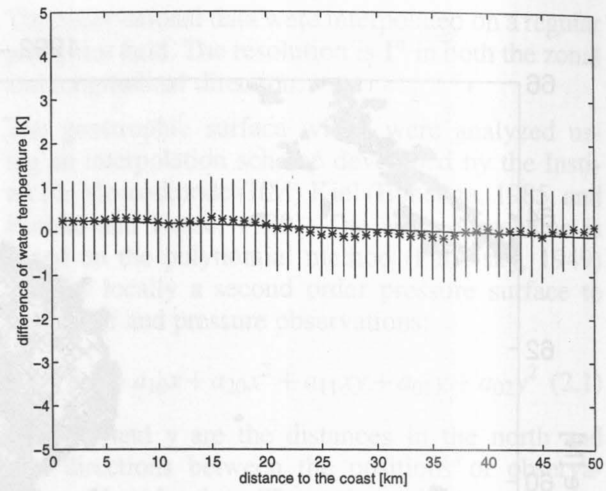

Figure 3: Systematic deviations of analyzed water temperatures from ship observations as a function of the distance to the coast for the period from January 1992 to December 1994 and the Baltic Sea. Analyzed temperatures were interpolated linearely on positions of ship observations; known biases of ship measurements of water temperatures (Kent et al., 1993) were taken into account. Standard deviations are indicated by the vertical bars. The full line gives the results of a linear regression.

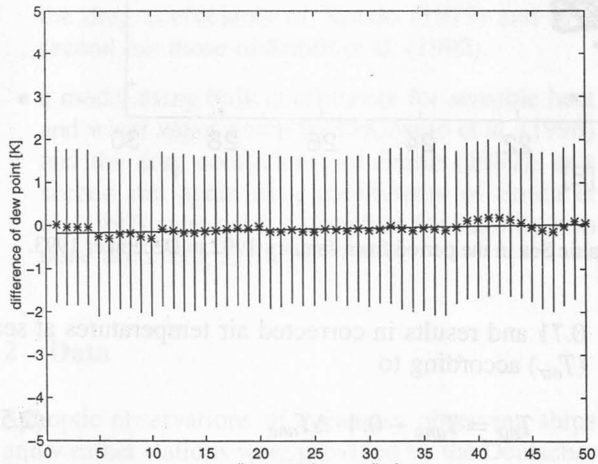

Figure 4: Systematic deviations of analyzed dew point temperatures from ship observations as a function of the distance to the coast for the period from January 1992 to December 1994 and the Baltic Sea. Analyzed temperatures were interpolated linearly on positions of ship observations, known biases of ship measurements of wet bulb temperatures (Isemer, 1987) were taken into account. Standard deviations are indicated by the vertical bars. The full line gives the results of a linear regression.

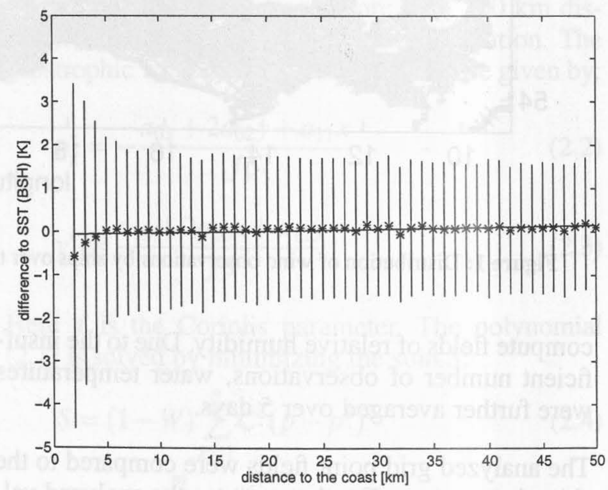

Figure 5: Systematic deviations of interpolated water temperatures to satellite estimates of the SST as a function of the distance from the coast for the period from January 1993 to December 1994 and the Baltic Sea. Root mean square deviation is indicated by the vertical bars. The full line gives the results of a linear regression.

analyzed and observed values are generally small. These are shown in Figures 2 to 4 as a function of the distance from the coast. For these comparisons known biases in ship measurements have been taken into account: an overestimation of 0.3°C for water temperature (Kent et al., 1993), 0.4°C for air temperature (Isemer, 1987) and 0.5°C for the wet bulb temperature (Isemer, 1987).

The interpolated air temperatures show a remaining small bias of 0.2°C; interpolated dew point temperatures are not biased. These results are independent of the distance to the coast (Figures 2 and 4). Interpolated water temperatures show a small bias depending on the distance to the coast (Figure 3). Noting the fact that ship measurements are usually taken at the engine input in 1 to 10 m depth (Kent et al., 1993), this bias might be caused by a selection of those sites where deep waters allow ships to go close to the shore. Indeed a comparison of analyzed water temperatures to satellite estimates of the SST (sea surface temperature), which were kindly provided from the Bundesamt für Seeschiffahrt und Hydrographie for the period 1993 to 1994, every 7 days, shows a constant bias of less than 0.2°C for all distances greater than 5 km from the coast. Only for distances less than 5 km from the coast a bias was found depending on the distance from the coast, but uncertainties are high as reflected in a significant increase of the root mean square (r.m.s.) error between analyzed water temperature and SST at those short distances from the coast. That reflects mainly the uncertainty of the satellite estimates of the SST in areas very close to the coast.

The river discharge into the Baltic Sea should also have an effect, but the high resolution fields of the SST, which were made available by the BSH, showed only a marginal effect of river outflow plumes on the SSTs.

In summary the biases in the analyzed data compared to ship observations taking known biases of ship observations into account, are small, but the influence on evaporation due to possible biases in the air and water temperature of about 0.2 °C each (Figures 3 and 4) and of a possible systematic error in estimated water temperatures close to the coast has to be checked, see below in Section 5.

3 Influence of the Coast on the Surface Wind Speed

As mentioned above the sparsity of observations allows only the calculation of sea level geostrophic winds. To estimate evaporation by a bulk parameterization 10 m wind speeds are required. In regions with complex terrain like coastal areas the best may be to use mesoscale models to get detailed information about the vertical and horizontal variation of the wind (e.g. Bergström, 1992). In this investigation we followed another approach. We have used ageostrophic coefficients which were estimated by a comparison of geostrophic winds with ship winds for the period

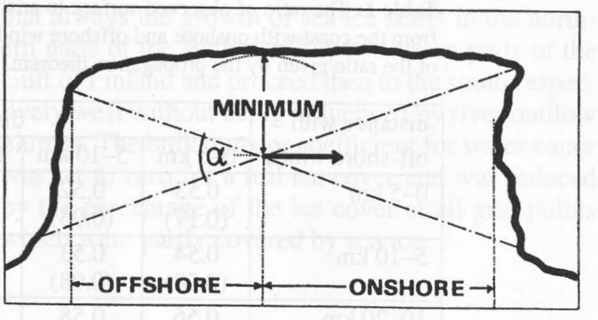

Figure 6: Distances from the coast with onshore and offshore winds and with winds blowing parallel to the coast, having onshore and offshore distances from the coast of more than 50 km each.

from 1992 to 1993. For this comparison it is important that there are two kinds of wind observations on voluntary observing ships: Direct measurements and Beaufort estimates of wind according to WMO 1100 scale (WMO, 1970). The wind speed from direct wind measurements is reduced to 10 m from an assumed average height of 20 m (Cardone et al., 1990) using the logarithmic wind profile; the Beaufort estimates are given for a height of 10 m (WMO, 1970).

These ageostrophic coefficients have been estimated as a function of distances from the coast, which are defined in this context as follows (Figure 6):

- a distance from the coast against the wind direction for onshore winds
- a distance from the coast in the wind direction for offshore winds
- a minimum distance from the coast for winds blowing more or less parallel to the coast.

Winds are assumed to blow parallel to the coast when the upwind and downwind distances from the coast are more than 50 km each.

The ratios of the 10 m wind speeds to the analyzed geostrophic surface wind speeds are given in Tables 1 and 2, smoothed by using a 1:2:1 filter. The error is given by the propagation theorem. For the open sea, which is taken to be 50 km or more from the coast, the ratio is 0.71. This agrees well with a ageostrophic ratio of 0.7 which is commonly accepted for the use at open seas. The asymmetry in the ageostrophic ratios for onshore and offshore wind conditions as a function of the distance from the coast was found also in other case studies in complex coastal areas with shallow waters (e.g. from Theunert (1986) or Barthelmie et al., 1996).

Table 1: The ratio of observed surface to analyzed geostrophic wind speed for classes of distances from the coast with onshore and offshore winds (Figure 6). The value in parenthesis represent error of the ratio given by the propagation theorem.

distance with off-shore winds	distance with onshore winds 0–5 km	5–10 km	10–20 km	20–30 km	30–50 km	> 50 km
0–5 km	0.53 (0.17)	0.52 (0.05)	0.54 (0.19)	0.56 (0.14)	0.59 (0.10)	0.56 (0.10)
5–10 km	0.54 (0.08)	0.53 (0.08)	0.56 (0.07)	0.59 (0.12)	0.60 (0.09)	0.59 (0.06)
10–20 km	0.56 (0.11)	0.58 (0.08)	0.61 (0.09)	0.62 (0.07)	0.62 (0.06)	0.62 (0.05)
20–30 km	0.58 (0.21)	0.59 (0.16)	0.61 (0.10)	0.63 (0.09)	0.64 (0.08)	0.65 (0.05)
30–50 km	0.61 (0.13)	0.62 (0.07)	0.65 (0.08)	0.65 (0.06)	0.66 (0.06)	0.67 (0.04)
> 50 km	0.63 (0.16)	0.64 (0.07)	0.67 (0.07)	0.67 (0.07)	0.68 (0.04)	0.71 (0.03)

Table 2: The ratio of observed surface to analyzed geostrophic wind speed for classes of minimum distances from the coast with winds blowing parallel to the coast (Figure 6). The errors are given by the propagation theorem.

distance	0–5 km	5–10 km	10–20 km	20–30 km	30–50 km	> 50 km
ratio	0.66	0.70	0.73	0.73	0.71	0.71
r.m.s. error	0.11	0.10	0.04	0.03	0.03	0.03

It should be mentioned that the changes of the ageostrophic ratios as a function of the distance from the coast for onshore wind conditions are typical for areas like the Baltic Sea, where the waters are shallow close to the coasts. This causes an increase in the roughness of the sea surface due to changes of the wave age in some distances from the coast (Smith et al., 1992). For offshore wind conditions the effect of changing surface roughnesses due to changes in wave age does not depend on limited water depth only, it is mainly caused by the limited fetch. Additionally the effect of changing surface roughness is superposed by the advection of land born turbulence in case of offshore wind conditions (e.g. Behrens, 1993).

Generally the approach of using ageostrophic coefficients to derive 10 m wind speeds from geostrophic winds includes in a statistical sense effects like land sea breezes and low level jets typical for the Baltic Sea area. Low level jets were observed and investigated for the Baltic Sea area by Bergström and Smedman (1995). These occur for stable conditions which are frequent in spring and early summer.

Validation of the 10 m wind fields was done using independent data from 1994. For 1994 about 8300 observations are at our disposal, which were not used for estimating the ageostrophic ratios. The comparison was done in terms of Weibull statistics. An example is given in Figure 7. The Weibull distributions of analyzed and observed wind speeds agree well even for higher wind speeds.

4 Ice

Ice covers the northern Baltic Sea regularly during winter time. Because ice hampers evaporation information on its distribution is needed. This was obtained as follows.

For the winter seasons 1992/1993 and 1993/1994 ice maps (Bundesamt für Seeschiffahrt und Hydrographie, 1992/1993) were at our disposal. The ice information on these maps was compared with the interpolated water temperatures. The results are given in Figure 8. At water temperatures below 0.7°C we had 63% of all cases with an ice coverage of 9 tenth or more, on the other hand we had 63% of all cases with open seas adjacent within of a distance of 1° latitude/longitude to areas covered with sea ice at water temperatures higher than 1.5°C. Thus, we assumed a total ice cover at analyzed water temperatures less or equal 0.7° C, and open waters at analyzed water

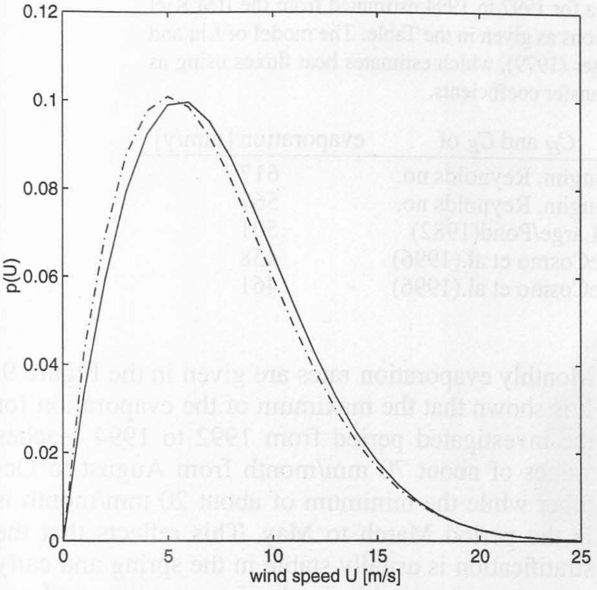

Figure 7: Weibull-function fitted to observed (full line) and analyzed (dashed dotted line) surface wind speeds at 10 m height for the year 1994 over the Baltic Sea extending from 15°-21°E and 54°-59°N.

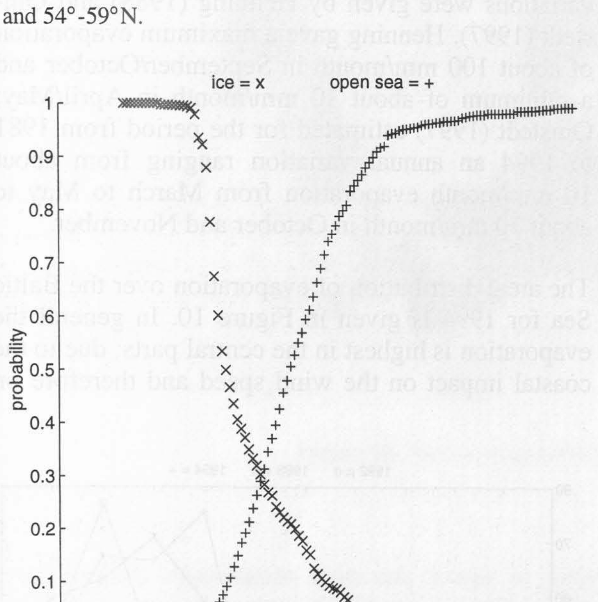

Figure 8: Probability of the occurrence of sea ice (x) and open water (+) as a function of analyzed water temperatures for the period from January 1992 to December 1993.

temperatures greater or equal 1.5°C. For the interval from 0.7 to 1.5°C a linear change of the ice cover was assumed as suggested as a reasonable approximation by Figure 8. The effect of river outflow on the occurence of sea ice due to reduced salinities seems to be necligible because the ice maps of the BSH show that always the growth of sea ice starts in the northern parts of the Bothnian Bay or eastern parts of the Gulf of Finland and proceed then to the south respectively west without being influenced by river outflow plumes. The bulk transfer coefficient for water vapor was set to zero for a full ice cover and was reduced by the percentage of the ice cover at all grid points which were partly covered by sea ice.

5 Evaporation over the Baltic Sea

As mentioned above for this study evaporation over the Baltic Sea was estimated from interpolated fields using a bulk parameterization. Possible reasons for errors might be systematic errors in the interpolated fields and the selected boundary layer parameterization. Also the bulk transfer coefficients themselves are only known with accuracies of about 10% (e.g. Laubach and Teichmann, 1996).

Therefore we carried out a series of calculations using different boundary layer schemes and bulk transfer coefficients. The resulting mean annual evaporation of the three year period ranges from 458 to 617 mm/y (Table 3). The model of Liu, Katsaros and Businger (1979) in its version from Liu and Blanc (1984) showed extremely high evaporation rates when drag coefficients of Kondo (1975) were used. They are about 23% higher than evaporation rates resulting from applying the scheme of Large and Pond (1981 and 1982) to the data. Using the drag coefficients of Smith et al. (1992) instead of those given by Kondo reduced the difference from Large and Pond to 13%. On the other hand estimates of evaporation using a boundary layer parameterization according to Smith (1988) with a drag coefficient adopted from Smith (1980) and bulk transfer coefficients for sensible heat and water vapor given by DeCosmo et al. (1996) resulted in about 9% less evaporation than based on Large and Pond. Using the drag coefficient of Smith et al. (1992) did not have a significant influence on the results. To investigate other possible uncertainties in estimated turbulent fluxes as mentioned above, in the following the boundary layer parameterization according to Large and Pond (1981 and 1982) is used.

To check the influence of possible biases in the interpolated fields, an overestimation of 0.2°C in air and water temperature has been applied as well as a possible bias in near coastal water temperatures as shown in Figure 5. The resulting annual evaporation is then 471 mm/y compared to 501 mm/y using the Large and Pond model. Thus, the resulting uncertainty due

Table 3: Mean annual evaporation over the Baltic Sea for 1992 to 1994 estimated from the IfM Kiel analysis using different boundary layer parameterizations as given in the Table. The model of Liu and Blanc refer to the model of Liu, Katsaros and Businger (1979), which estimates heat fluxes using as input roughness Reynolds numbers instead of bulk transfer coefficients.

Model of	C_D of	C_H and C_E of	evaporation [mm/y]
Liu/Blanc(1984)	Kondo(1975)	roughn. Reynolds no.	617
Liu/Blanc(1984)	Smith et al.(1992)	roughn. Reynolds no.	567
Large/Pond(1981,82)	Large/Pond(1981)	Large/Pond(1982)	501
Smith(1988)	Smith(1980)	DeCosmo et al.(1996)	458
Smith(1988)	Smith et al.(1992)	DeCosmo et al.(1996)	461

to possible systematic errors in the data is smaller than uncertainties due to different parameterizations of the turbulent fluxes. Both values are very close to an annual evaporation rate of 498 mm/y over the total Baltic Sea area as given by Henning (1988) for the reference period 1862–1978. Henning too used in his study a bulk parameterization, applying bulk coefficients given by Bunker (1976). To interprete the results it is important to know that a study of Isemer and Hasse (1987) showed that the use of the bulk transfer coefficients of Bunker results in an overestimation of evaporation. Sea ice was taken into account by Henning as climatological mean of the ice coverage for the different subbasins of the Baltic Sea.

The average annual evaporation rate using the parameterization of Large and Pond (1981 and 1982) for 1992 to 1994 agrees very well with results of a study from Omstedt (1997) giving an mean annual evaporation for the same period over the Baltic Sea and the Kattegat of about 512 mm/y. Omstedt too used a bulk parameterization with bulk transfer coefficients given by Friehe ans Schmitt (1976). Stability effects are included only by a coarse approach using bulk transfer coefficients for evaporation of 0.0012 for stable, 0.0013 for neutral to slightly unstable and 0.0020 for unstable conditions (Ohmstedt et al., 1997), where stability was estimated from the bulk products of wind speed and temperature difference, while the present study uses boundary layer parameterization schemes as given above in Section 1 based on Monin Obukhov similarity theory.

Sea ice was modelled by routines included in a Baltic Sea model (Omstedt et al, 1997), which took for example changes in surface salinity by precipitation and evaporation into account.

Due to differences in definitions of the subbasins a direct comparison is not possible, but generally evaporation rates given by Ohmstedt are lower in areas which were partly covered by ice and higher in the central parts of the Baltic Sea for the period from 1992 to 1994.

Monthly evaporation rates are given in the Figure 9. It is shown that the maximum of the evaporation for the investigated period from 1992 to 1994 reaches values of about 70 mm/month from August to October while the minimum of about 20 mm/month is in the period March to May. This reflects that the stratification is usually stable in the spring and early summer and unstable in the late summer and autumn. It showed that the year to year differences for the choosen period were small. Similar annual variations were given by Henning (1988) and Omstedt (1997). Henning gave a maximum evaporation of about 100 mm/month in September/October and a minimum of about 10 mm/month in April/May; Omstedt (1997) estimated for the period from 1981 to 1994 an annual variation ranging from about 10 mm/month evaporation from March to May to about 70 mm/month in October and November.

The areal distribution of evaporation over the Baltic Sea for 1994 is given in Figure 10. In general the evaporation is highest in the central parts; due to the coastal impact on the wind speed and therefore on

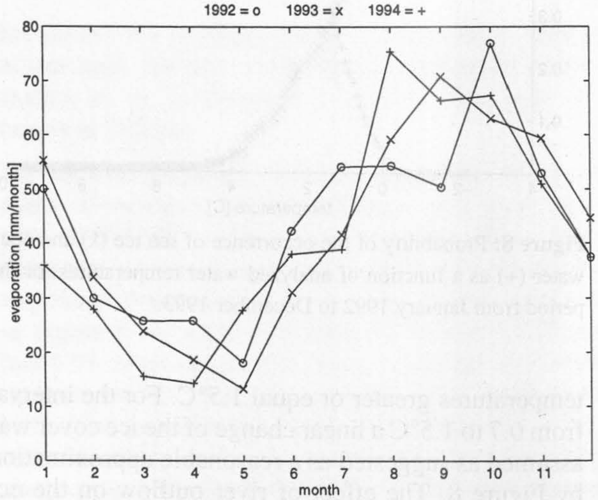

Figure 9: Monthly evaporation in the period from January 1992 to December 1994 over the Baltic Sea.

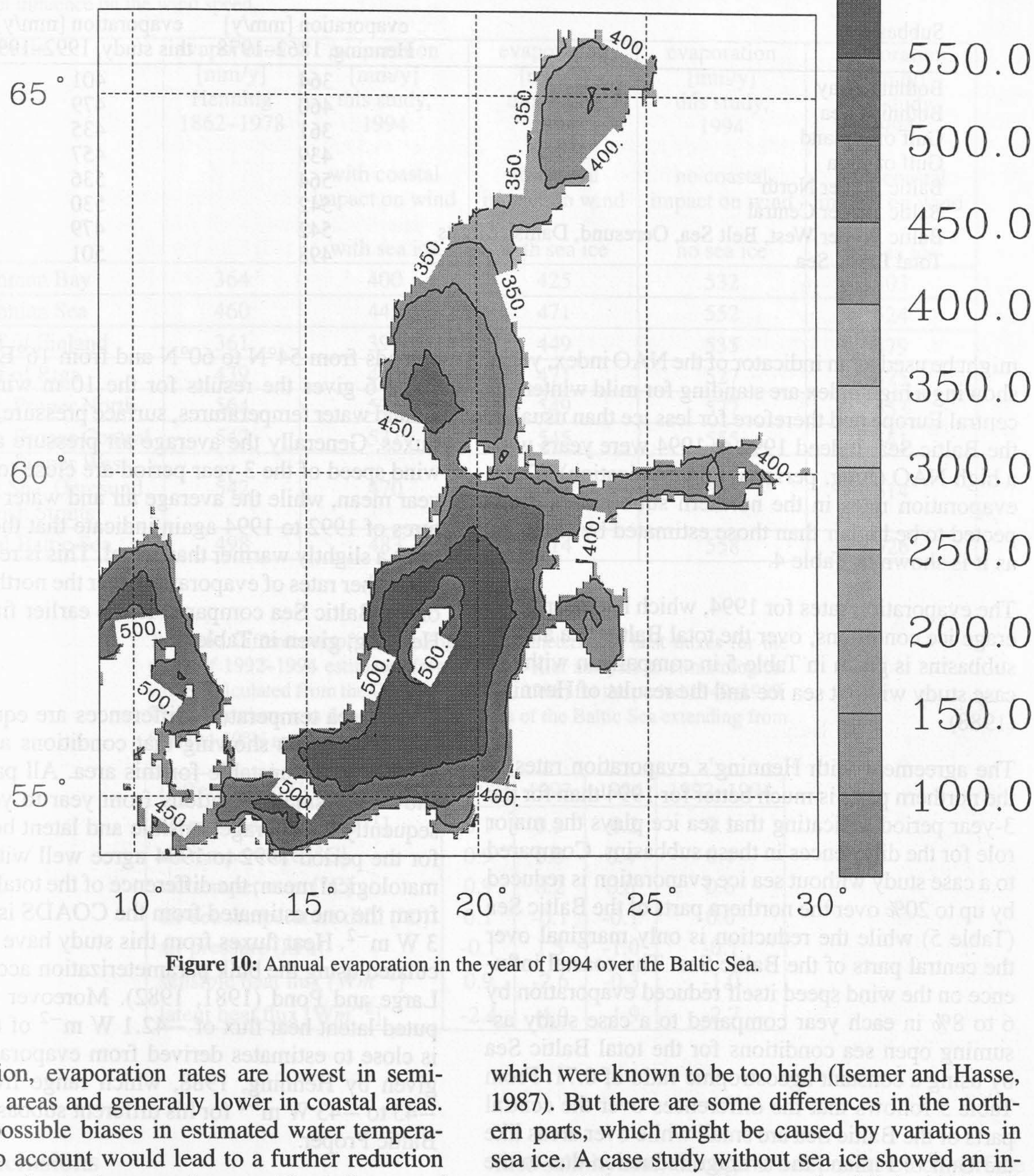

Figure 10: Annual evaporation in the year of 1994 over the Baltic Sea.

evaporation, evaporation rates are lowest in semi-enclosed areas and generally lower in coastal areas. Taking possible biases in estimated water temperatures into account would lead to a further reduction of evaporation in the coastal zones. The influence of sea ice decreases evaporation mainly in parts of the Bothnian Bay and Sea as well as in the Gulfs of Finland and Riga.

For different subbasins of the Baltic Sea the three-year annual average evaporation is compared in Table 4 to previous results of Henning (1988).

The agreement is good for the central parts of the Baltic Sea, the small differences might be due to bulk coefficients of Bunker (1976) used by Henning, which were known to be too high (Isemer and Hasse, 1987). But there are some differences in the northern parts, which might be caused by variations in sea ice. A case study without sea ice showed an increase of the evaporation rates by 1% in 1992, 2% in 1993 and 7% in 1994. It should be noted here that only in 1994 the extension of the sea ice is comparable to the climatological average (Bundesamt für Seeschiffahrt und Hydrographie, 1991); in 1992 and 1993 there was less ice than usual. Similar results were obtained by Ohmstedt et al. (1997), they calculated an average reduction of 8 % of the evaporation by sea ice. For readers interested in the North Atlantic Oscillation (NAO) it should be mentioned that to the authors' opinion the extension of sea ice

Table 4: Evaporation over subbasins of the Baltic Sea in the years of 1992–1994 estimated from the IfM Kiel analysis, compared to previous results given by Henning (1988) for the period 1862–1978.

Subbasin	evaporation [mm/y] Henning, 1862–1978	evaporation [mm/y] this study, 1992–1994
Bothnian Bay	364	401
Bothnian Sea	460	479
Gulf of Finland	361	435
Gulf of Riga	439	457
Baltic Proper North	564	536
Baltic Proper Central	542	530
Baltic Proper West, Belt Sea, Oeresund, Danish Straits	542	479
Total Bàltic Sea	498	501

might be used as an indicator of the NAO index, years showing a high index are standing for mild winters in central Europe and therefore for less ice than usual in the Baltic Sea. Indeed 1992 to 1994 were years with a high NAO (Jung, personal communication). Thus, evaporation rates in the northern subbasins are expected to be higher than those estimated by Henning as it is shown in Table 4.

The evaporation rates for 1994, which had nearly average ice conditions, over the total Baltic Sea and its subbasins is given in Table 5 in comparison with the case study without sea ice and the results of Henning (1988).

The agreement with Henning's evaporation rates in the northern parts is much better for 1994 than for the 3-year period indicating that sea ice plays the major role for the differences in these subbasins. Compared to a case study without sea ice evaporation is reduced by up to 20% over the northern parts of the Baltic Sea (Table 5) while the reduction is only marginal over the central parts of the Baltic Sea. The coastal influence on the wind speed itself reduced evaporation by 6 to 8% in each year compared to a case study assuming open sea conditions for the total Baltic Sea by using a constant ageostrophic ratio of 0.71. From Table 5 follows that the differences over the central parts of the Baltic Sea are small while over areas like the Gulf of Finland the average reduction due to the coastal influence on the wind speed reaches values of about 12%. In view of this comparison the question arises, whether such studies over short periods give representative results. Thus, it needs to be checked, whether these years are typical for climatological conditions of the Baltic Sea. To investigate this, long term averages given by Lindau (1998) were used for comparison, which were derived from the Comprehensive Ocean and Atmosphere Data Set (COADS) for the period from 1940 to 1979. The comparison was done for a limited area of the Baltic Sea, which extends from 54°N to 60°N and from 16°E to 22°E. Table 6 gives the results for the 10 m wind speed, air and water temperatures, surface pressure, and heat fluxes. Generally the average air pressure and 10 m wind speed of the 3 year period are close to the long year mean, while the average air and water temperatures of 1992 to 1994 again indicate that those years were a slightly warmer than usual. This is reflected in the higher rates of evaporation over the northern parts of the Baltic Sea compared to the earlier findings of Henning, given in Table 4.

The air-sea temperature differences are equal to the long-term mean showing that conditions are on average slightly unstable for this area. All parameters show only small variations from year to year. Consequently the average sensible and latent heat fluxes for the period 1992 to 1994 agree well with the climatological mean; the difference of the total heat flux from the one estimated from the COADS is less than 3 W m^{-2}. Heat fluxes from this study have been calculated using the bulk parameterization according to Large and Pond (1981, 1982). Moreover the computed latent heat flux of -42.1 W m^{-2} of this study is close to estimates derived from evaporation rates given by Henning, 1988, which range from about -45 to -43 W m^{-2} for his different subbasins of the Baltic Proper.

In summary it can be stated that the conditions during the three years' period can be regarded as representative only for the central parts of the Baltic Sea, where sea ice plays an important role only in severe winters like 1987 (Ohmstedt et al., 1997). Some uncertainties exist still for the northern subbasins due to a highly variable amount of sea ice, but because of their small spatial extension the influence of variations in sea ice cover on average evaporation compared to average ice conditions should be small.

Table 5: Evaporation over subbasins of the Baltic Sea for the year of 1994 estimated from the IfM Kiel analysis, compared to previous results given by Henning (1988) for the period 1862–1978 and to case studies without sea ice and without a coastal influence on the wind speed.

Subbasin	evaporation [mm/y] Henning 1862–1978	evaporation [mm/y] this study, 1994 with coastal impact on wind with sea ice	evaporation [mm/y] this study, 1994 no coastal impact on wind with sea ice	evaporation [mm/y] this study, 1994 no coastal impact on wind no sea ice	evaporation [mm/y] this study, 1994 with coastal impact on wind no sea ice
Bothnian Bay	364	400	425	532	503
Bothnian Sea	460	445	471	552	524
Gulf of Finland	361	399	449	535	479
Gulf of Riga	439	422	471	527	475
Balt. Proper North	564	525	549	577	553
Balt. Proper Central	542	531	545	555	541
Balt. Proper West, Belt Sea, Oeresund, Danish Straits	542	470	511	556	514
Total Baltic Sea	498	483	514	558	526

Table 6: Differences of meteorological parameters and heat fluxes for the years of 1992–1994 estimated from the IfM Kiel analysis to climatological values calculated from the COADS (Lindau, 1998) for the period 1940–1989. The comparison was done for a limited area of the Baltic Sea extending from 54°N to 60°N and from 16°E to 22°E.

Difference to COADS of	1992	1993	1994	1992–1994
10 m wind speed [ms^{-1}]	0.1	0.3	-0.2	0.1
air temperature [°C]	0.9	0.0	0.4	0.4
sea temperature [°C]	0.9	0.2	0.6	0.6
air-sea temperature diff. [°C]	0.1	-0.1	-0.1	0.0
air pressure [hPa]	-0.1	1.5	-1.0	-0.1
sensible heat flux [Wm^{-2}]	0.9	-2.6	-0.3	-1.0
latent heat flux [Wm^{-2}]	-2.4	-4.0	-1.9	-2.7

6 Conclusions

The results of the evaporation over the total Baltic Sea from this study, taking both sea ice and the coastal influence on the wind speed into account, are very close to earlier estimates given by Henning (1988) or Omstedt (1997). It is shown that systematic uncertainties of the order of 10% and more still exist depending only on the used parameterization schemes of turbulent fluxes. Furthermore uncertainty in evaporation will affect for example the surface salinity and, through it's dependence on surface salinity, also the generation of sea ice.

A comparison to climatological estimates of the meteorological variables and the resulting heat fluxes showed that even a three year period such as 1992/94 was useful for estimating the evaporation over areas like the total Baltic Sea, but to get a better knowledge about the spatial and annual variability more years are needed. To estimate temporal and spatial variations of evaporation it is necessary to collect much more ship observations than were available or, as it was done in this study, to make use of data interpolation, which would improve too, if more ship observations would be available.

Furthermore the importance of sea ice for the evaporation of the Baltic Sea illustrates that the development of coupled high resolution ocean, sea ice and atmospheric models will be a very useful tool to improve our knowledge about evaporation, one of the main goals of BALTEX.

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